

# PROPAGATION OF GAMMA-RAYS IN MASSIVE BINARY CEN X-3: INTERACTION OF CASCADE GAMMA-RAYS WITH THE MASSIVE STAR

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## ABSTRACT

We consider the propagation of very high energy (VHE) gamma-rays in the radiation field of the massive star of binary system Cen X-3. VHE gamma-rays or electrons, injected by the compact object close to the surface of a massive companion, develop inverse Compton  $e^\pm$  pair (ICS) cascades. Based on the Monte Carlo simulations, we obtain the fraction of secondary cascade photons which collide with the surface of the massive companion in Cen X-3 system. The distribution of photons falling on the surface of the massive star is investigated. These photons interact with the atmosphere of the star and should excite different  $\gamma$ -ray lines (nuclear,  $e^\pm$  annihilation line). We estimate that these  $\gamma$ -ray lines can be likely detected by the INTEGRAL telescopes.

Key words: gamma-rays; propagation; massive binaries: Cen X-3.

## 1. INTRODUCTION

Observations of some massive binaries suggest that they may be sources of  $\gamma$ -rays in the GeV and TeV energy range. For example the massive X-ray binary system, Cen X-3, containing a neutron star with a 4.8 s period in a 2.09 day orbit around an O-type supergiant, has been detected above 100 MeV  $\gamma$ -rays by the EGRET detector on the Compton Observatory (Vestrand et al. 1997). There are evidences that observed  $\gamma$ -ray emission at these energies has a form of outbursts and is modulated with a 4.8 s period of the pulsar. Based on the observations in late 80's, two groups (Brazier et al. 1990, North et al. 1990) reported Cherenkov detection of positive signal at TeV energies from Cen X-3 at an orbital phase of  $\sim 0.75$ , which is modulated with a period of the pulsar. This emission has been localized by Raubenheimer & Smit (1997) to a relatively small region between the pulsar orbit and the surface of a massive companion which may be the accretion wake or the limb of the star. More recently the Durham group

has detected a persistent flux of  $\gamma$ -rays above 400 GeV on a lower level than previous reports (Chadwick et al. 1998, 1999a,b). No evidence of correlation with the pulsar or orbital periods has been found and no evidence of correlation with the X-ray flux has been detected (Chadwick et al. 1999a,b).

The problem arises if such TeV photons injected close to the surface of the massive star (e.g. by the compact object) can escape from the soft radiation field of the massive star in the binary system Cen X-3. The computations of the optical depth for TeV photons in the radiation fields of such type massive stars show that the absorption of TeV photons should be significant (e.g. Protheroe & Stanev 1987, Moskalenko et al. 1993, Bednarek 1997). Recently we have performed Monte Carlo simulations of cascades initiated by  $\gamma$ -ray photons and electrons with different energy and angular distributions, which are injected by the discrete source in the radiation field characteristic for the Cen X-3 system (Bednarek 2000). The spectra of escaping  $\gamma$ -ray photons and their light curves have been obtained and discussed in the context of recent GeV and TeV observations. In this paper we compute the  $\gamma$ -ray power and spectra of photons which fall onto the surface of the massive star in Cen X-3. These photons should excite different  $\gamma$ -ray nuclear lines and also  $e^\pm$  annihilation line. Their detection by INTEGRAL telescopes should give independent information on high energy processes which seems to occur in Cen X-3 system. The following parameters for the massive binary Cen X-3 are assumed: the radius of the O star  $r_s = 8.6 \times 10^{11}$  cm, its surface temperature  $T_s = 3 \times 10^4$  K, the binary star separation  $a = 1.2 \times 10^{12}$  cm (Krzemiński 1974).

## 2. GAMMA-RAYS FROM ICS CASCADE

Let us assume that  $\gamma$ -ray photons are injected by the compact object which is on an orbit around the star with the parameters characteristic for Cen X-3 system. These photons may create  $e^\pm$  pair in collision with the soft star photon (Bednarek 2000). The

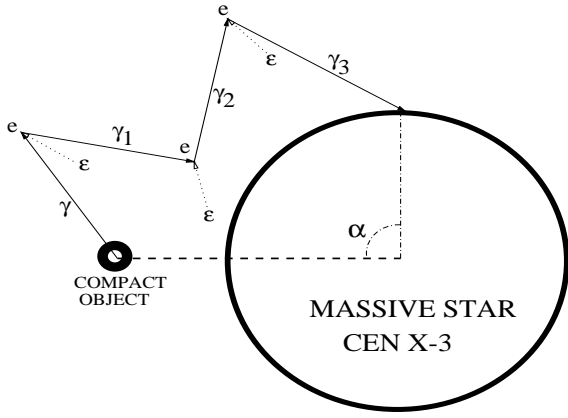


Figure 1. Schematic picture of the cascade initiated by a primary gamma-ray ( $\gamma$ ) in the radiation field of a massive star. Gamma-ray photon, injected by the compact object or produced by primary electron, creates  $e^\pm$  pairs ( $e$ ) in the interaction with a soft star photon  $\epsilon$ . The secondary  $e^\pm$  pairs, by scattering soft star photons, create secondary gamma-rays ( $\gamma_1, \gamma_2, \gamma_3$ ). Some of them ( $\gamma_3$ ) may fall onto the surface of the massive star.

secondary pairs can next produce ICS  $\gamma$ -rays, initiating in this way the ICS cascade in the massive star radiation which is seen anisotropic in respect to the location of the injection place of the primary photons or electrons.

The propagation of secondary pairs inside the binary system is determined by the strength and the geometry of the magnetic field which in general may be very complicated. We analyze the case in which the random component of the magnetic field isotropize secondary cascade  $e^\pm$  pairs close to the place of their creation before they next scatter soft photon from the massive star. This condition is met if the mean free path for ICS process is longer than the Larmor radius of secondary pairs in the local magnetic field (see discussion and condition for that to occur in Bednarek 1997). We neglect also the synchrotron losses of secondary pairs in respect to their ICS losses on star photons. This can be done for the values of the magnetic field below certain limit (see Eq. 3 in Bednarek 1997). The bremsstrahlung losses of pairs in matter with the star wind densities characteristic for the OB stars are negligible.

In the previous paper (Bednarek 2000), we show the details of the Monte Carlo simulations and concentrate on the photons which escape from the binary system. However significant part of secondary cascade photons should collide with the massive star. The distribution of these photons on the star surface, their spectra and the fraction of photon power which fall onto the surface in respect to the power of all produced cascade photons is investigated in this paper. The considered picture is shown in Fig. 1.

We concentrate on two cases which were already discussed in Bednarek (2000), i.e. the case of isotropic

injection of electrons and isotropic injection of photons with a power law spectrum and index -2. Electrons with such distribution can be accelerated at the shock front created in collision of the pulsar wind with the surrounding matter as proposed in the model by Kennel & Coroniti (1984). If the compact object (neutron star) is surrounded by dense cocoon created by matter accreting spherically-symmetric or by the accretion disk, then the  $\gamma$ -ray photons should be injected into the volume of the binary system. Based on our simulations we show in Figs. 2a and b the distribution of secondary photons on the surface of the massive star and the distribution of the  $\gamma$ -ray power of these secondary photons as a function of the cosine angle  $\alpha$ , measured from the direction defined by the centers of the massive star and the compact object. Note that this distribution is axially symmetric (see Fig. 1).

The numbers of secondary photons and their power falling onto the massive star drop strongly with the angle  $\alpha$ . Only a small number of photons is able to fall onto the opposite side of the massive star than the location of the compact object (the source of primary particles initiating the cascade), i.e. at cosine angles less than  $\cos \alpha = 0$ . This angular distribution of falling photons is much sharper than the angular distribution of cascade photons escaping from the system. These interesting features are due to the type of the considered cascade process in which the secondary  $e^\pm$  pairs are isotropized by the random magnetic field. These pairs produce secondary ICS photons moving towards the massive star surface with higher probability. However for secondary photons it is easier to escape from the system on the opposite side of the massive star than collide with the surface of the massive star on the opposite side. There are also differences in distributions of secondary photons on the massive star surface in the case of injection of primary photons and electrons (compare dotted and full histograms in Figs. 2a and b). The distribution of secondary photons from cascades initiated by primary photons shows higher number of secondary photons falling onto the opposite side of the massive star and on the surface of massive star just below the compact object the than in the case of injection of primary electrons. This is due to the fact that primary photons produce first generation of  $e^\pm$  pairs in quite extended region around the compact object in comparison to the point like injection of primary electrons in the second case. We show also in Figs. 3a and b the spectra of secondary photons falling onto the massive star in both discussed cases for different range of cosine angles  $\alpha$ . As expected, the secondary photons with the highest energies fall mainly onto the massive star for small angles  $\alpha$ . On the opposite side of the massive star fall only secondary photons with relatively low energies.

We estimate also the ratio of power of secondary photons which fall onto the massive star to power of photons which escape from the system. In the case of injection of primary photons this ratio is equal to  $\sim 13\%$  and in the case of injection of primary elec-

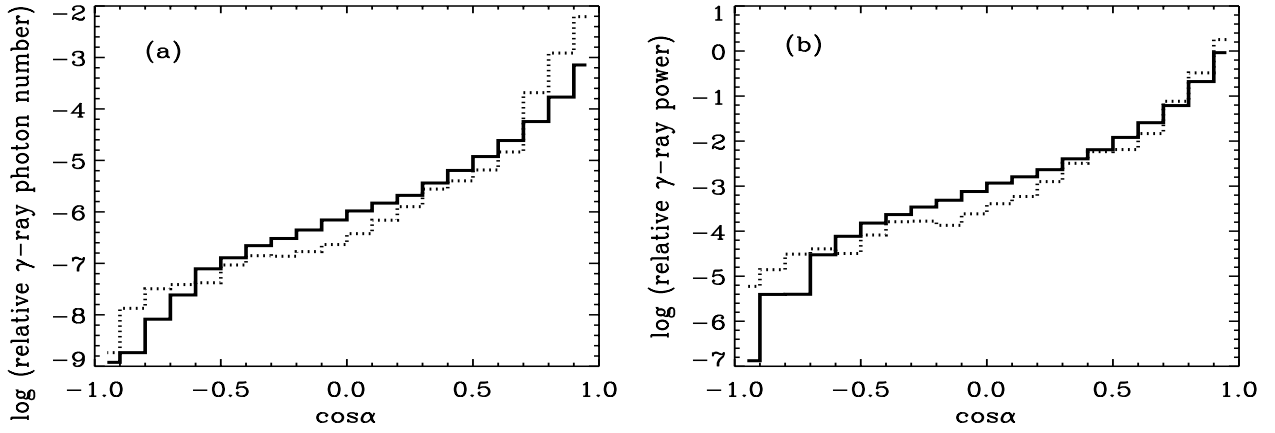


Figure 2. The number of  $\gamma$ -rays (a) and  $\gamma$ -ray power (b) falling on the surface of the massive star in Cen X-3 system. It is assumed that the point like source injects isotropically primary  $\gamma$ -rays (dotted histogram) or primary electrons (full) with a power law spectra and spectral index  $-2$ .

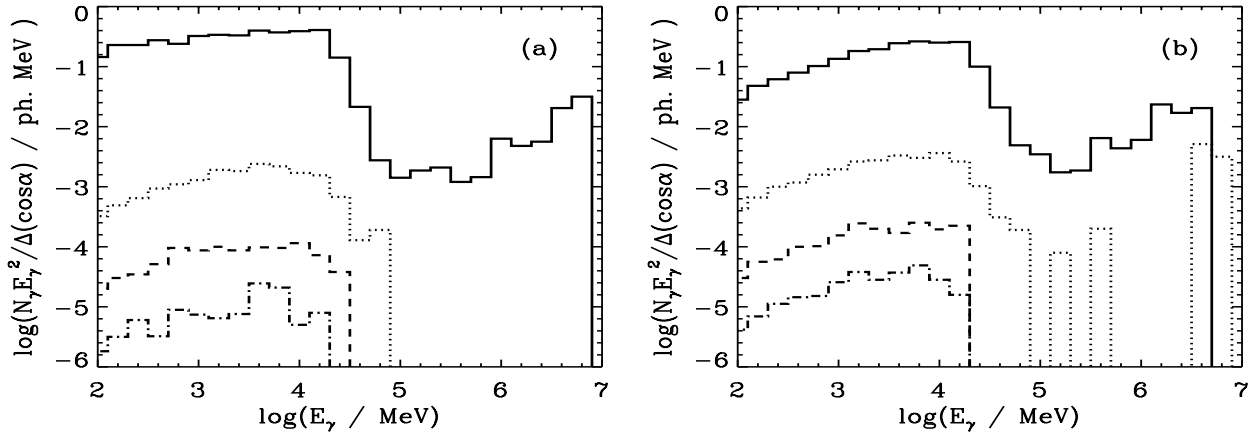


Figure 3. The spectra of  $\gamma$ -ray photons falling onto the surface of the massive star in Cen X-3 system within the cosine angle  $\alpha$ :  $\cos \alpha = 0.9 \leftrightarrow 1$  (full histogram),  $0.5 \leftrightarrow 0.6$  (dotted),  $0 \leftrightarrow 0.1$  (dashed), and  $-0.5 \leftrightarrow -0.4$  (dot-dashed). The primary electrons (a) and photons (b), with a power law spectrum and spectral index  $-2$ , are injected isotropically by the compact object at the distance of  $1.4$  radii from the massive star.

trons it is equal to  $\sim 40\%$ . In the case of primary electrons, this is much more than expected from simple geometrical considerations (the case of non-cascading photons) which predicts that only  $\sim 13\%$  of photons should fall into the star surface since this part of the sky is shaded by the massive star. In the case of primary photons, the non-cascading photons dominate and the ratios are comparable.

This results show that significant part of the  $\gamma$ -ray power observed from the binary system should be transferred onto the surface of the massive star. These  $\gamma$ -rays can heat the star and partially can be re-emitted in the form of nuclear lines and  $e^\pm$  annihilation line. Therefore we suggest that the binary systems of the Cen X-3 type can also produce  $\gamma$ -ray lines in the MeV energy range.

To find out what is the relation between this ex-

pected  $\gamma$ -ray line emission and the continuous emission, we compare in Figs. 4a,b and c the spectra of photons which fall onto the surface of the massive star at fixed angles  $\alpha$  with the spectra of secondary cascade photons which escape from the system at these same ranges of angles (see Bednarek 2000). Fig. 4a shows that the line emission should be the strongest when the compact object is in front of the massive star. Similar behaviour is expected for the escaping cascade  $\gamma$ -rays with energies above 100 GeV (ground Cherenkov telescopes). On the contrary, the highest fluxes of escaping cascade photons with energies above 100 MeV (space telescopes) are expected in the direction tangent to the massive star limb (see Fig. 4c). Therefore it is expected that the maximum of the  $\gamma$ -ray line light curve should not correspond to the maximum of the 100 MeV  $\gamma$ -ray continuous emission.

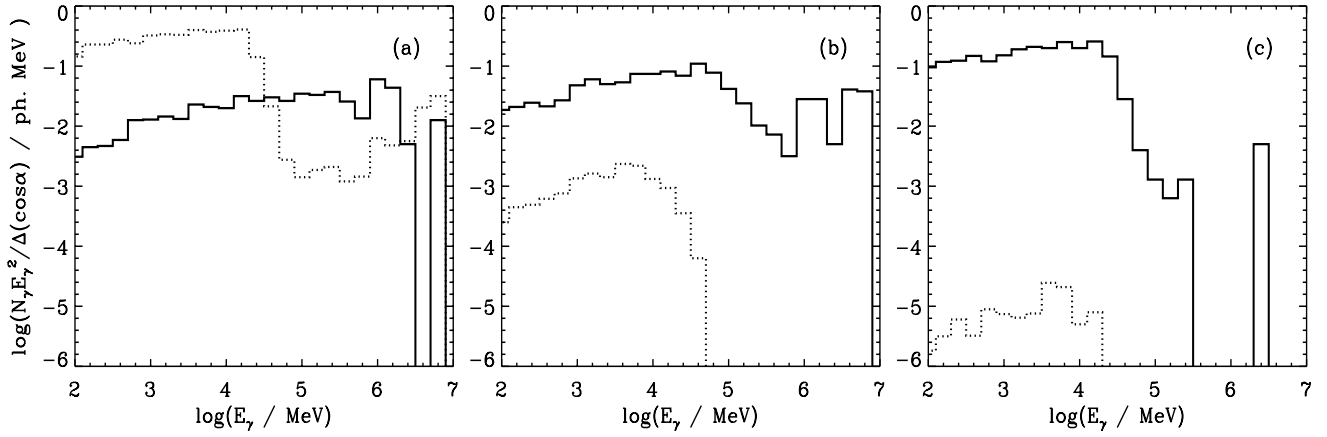


Figure 4. Comparison of the secondary  $\gamma$ -ray spectra which escape from the binary system Cen X-3 (full histograms) and which fall onto the surface of the massive star (dotted histograms) for these same cosine angles  $\alpha$  equal to  $\cos \alpha = 0.9 \leftrightarrow 1$ . (a),  $0.5 \leftrightarrow 0.6$  (b), and  $-0.5 \leftrightarrow -0.4$  (c). The primary electrons with a power law spectrum and spectral index -2. are injected by the compact object.

### 3. CONCLUSION

Assuming that VHE  $\gamma$ -ray photons or electrons are injected inside the binary system Cen X-3, as postulated by observations of this source in the GeV and TeV energy ranges, we consider the cascades initiated by these particles in the radiation field of the massive star in Cen X-3. The spectra of secondary photons, which escape from the system and fall onto the surface of the massive star, are obtained by using the Monte Carlo method. The photons which fall onto the massive star should excite the  $\gamma$ -ray nuclear lines and the  $e^\pm$  annihilation line. The maximum intensities of  $\gamma$ -ray line emission is expected when the compact object is in front of the massive star. On the contrary, the maximum emission of the 100 MeV emission is expected for direction tangent to the limb of the massive star. Therefore the  $\gamma$ -ray light curves observed at low and high energies should appear different.

Our model predicts that about  $13 \leftrightarrow 40\%$  of  $\gamma$ -ray power escaping from the system can be transferred to the surface of the massive star as a result of cascades in the binary system Cen X-3. The phase averaged  $\gamma$ -ray luminosity above 100 MeV, reported by the EGRET telescope, is  $\sim 5 \times 10^{36}$  erg s $^{-1}$  (Vestrand et al. 1997). Therefore about  $\sim 1 \leftrightarrow 2 \times 10^{36}$  erg s $^{-1}$  should fall onto the star. The INTEGRAL Spectrometer instrument will have narrow-line sensitivity of a  $5 \times 10^{-6}$  ph cm $^{-2}$  s $^{-1}$  at 1 MeV and continuum sensitivity  $1.5 \times 10^{-7}$  ph cm $^{-2}$  s $^{-1}$  at 1 MeV (<http://astro.estec.esa.nl/SA-general/projects/INTEGRAL>). It will be able to detect the 1 MeV  $\gamma$ -ray source emitting the power  $\sim 10^{35}$  erg s $^{-1}$  at the distance of Cen X-3 system equal to 8 kpc (Krzemiński 1974). Therefore the conversion efficiency of cascade photons into the  $\gamma$ -ray line photons on the surface of the massive star should be  $\sim 3 \leftrightarrow 10\%$ . This value does not seems to

be extraordinary. The detailed predictions for possible detection of such lines from Cen X-3 by the INTEGRAL telescopes will be considered in the future.

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